Surface Property of Passivation Layer on Integrated Circuit Chip and Solder Mask Layer on Printed Circuit Board

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***Abstract*—Adhesion of underfill to passivation layer on integrated circuit chip and solder mask layer on printed circuit board is critical to the reliability of an underfilled flip chip package. In this study, the surface properties of solder mask and four passivation materials: benzocyclobutene (BCB), polyimide (PI), silicon dioxide (SiO_2), and silicon nitride (SiN) were investigated. A combination of both wet and dry cleaning processes was very effective to remove contaminants from the surface. The element oxygen, introduced during O_2 plasma treatment or UV/O_3 treatment, led to the increase of the base component of surface tension. X-ray photoelectron spectroscopy (XPS) experiments confirmed the increase of oxygen concentration at the surface after UV/O_3 treatment. Wetting of underfill on passivation and solder mask was slightly improved at higher temperatures. Although UV/O_3 cleaning and O_2 plasma treatment significantly improved the wetting of underfill on passivation materials, they did not improve adhesion strength of epoxy underfill to passivation. Therefore, the wetting was not the controlling factor in adhesion of the system studied.**

***Index Terms*—Contact angle, O_2 plasma, passivation, solder mask, surface tension, surface treatment, UV/O_3, XPS.**

I. Introduction

CONTACT angle measurement is the most convenient and rapid method to probe the surface constitution of a solid. It can sense the force of monolayer (5–10 Å), thus it is extremely surface sensitive. Contact angle is related to the surface tension (also called surface energy) of the solid vapor interface (γ_{sv}), the liquid vapor interface (γ_{lv}), and solid liquid interface (γ_{sl}). Their relationship is given by Young's equation

$$\gamma_{sv} = \gamma_{sl} + \gamma_{lv} Cos(\theta) \tag{1}$$

or

$$\gamma_{lv} Cos(\theta) = \gamma_{sv} - \gamma_{sl}. \tag{1a}$$

Contact angle value can be divided into three regions:

$$\theta = 0^\circ, \quad 0^\circ < \theta < 90^\circ, \quad \theta \geq 90^\circ.$$

When the contact angle of a liquid on a solid is 0°, liquid film can be formed by the decreasing of the total free energy $(\gamma_{lv} + \gamma_{sl} - \gamma_{sv} < 0)$. When θ is between 0° and 90°, $\gamma_{sv} - \gamma_{sl}$ is smaller than the surface tension of the liquid, thus liquid film can not be formed spontaneously. Nevertheless,$\gamma_{sv} - \gamma_{sl}$ is still positive, so there is a decrease in free energy on converting the solid-vapor interface to a solid-liquid interface, thus asperities on the solid surface can be filled by the advancing liquid. When the contact angle is greater than 90°, $\gamma_{sv} - \gamma_{sl}$ is negative, and the surface asperities cannot be filled by the advancing liquid.

It was proposed that the surface tension is composed of three components [1], [2] the Lifshitz-van der Waals component (γ^{LW}) including electromagnetic interaction, oscillating temporary dipoles interaction, and permanent and induced dipoles interaction; the Lewis acid component (γ^+); and the Lewis base component (γ^-). Their relationship is given by

$$\gamma = \gamma^{LW} + 2(\gamma^+\gamma^-)^{\frac{1}{2}}. \tag{2}$$

Thermodynamic work of adhesion (W_a, also called physical adhesion) is the reversible work required to separate a unit area of two contacting phases. It is composed of LW component (W^{LW}) and acid-base component (W^{AB}), and it is directly related to the surface tension. The nongeometric combining rule was proposed [3]

$$W_a = W^{LW} + W^{AB} = \gamma_1 + \gamma_2 - \gamma_{12} \tag{3}$$

$$W^{LW} = 2\left({\gamma_1}^{LW}{\gamma_2}^{LW}\right)^{\frac{1}{2}} \tag{4}$$

$$W^{AB} = 2\left({\gamma_1}^+{\gamma_2}^-\right)^{\frac{1}{2}} + 2\left({\gamma_1}^-{\gamma_2}^+\right)^{\frac{1}{2}}. \tag{5}$$

Where γ_1 and γ_2 are surface tension of component 1 and component 2 in the medium, respectively, and γ_{12} is the interfacial tension between the two components. It was suggested that surface modification can alter the acid-base component rather than LW component, and thus the work of adhesion can be enhanced by surface modification through increasing the acid-base interaction [4].

The three-liquid-probe was proposed to measure the surface tension and its three components of a solid surface [1], [3], [5]. Water and ethylene glycol (EG) can be used as two polar liquids, and diiodomethane is frequently used as the apolar liquid. The surface tension and its three components for these probe liquids are shown in Table I.

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TABLE I
SURFACE TENSION OF THREE PROBE LIQUIDS

Liquid	γ mJ/m^2	γ^{LW} mJ/m^2	γ^+ mJ/m^2	γ^- mJ/m^2
CH_2I_2	50.8	50.8	0	0
H_2O	72.8	21.8	25.5	25.5
EG	47.9	29.0	1.9	47.0

The work of adhesion between a solid and a liquid can also be expressed by the following equation, deduced from (1) and (3)

$$W_A = \gamma_{lv} + \gamma_{sv} - \gamma_{lv} = \gamma_{lv}\,(1 + Cos(\theta))\,. \tag{6}$$

Thus, the three components of surface tension of a solid (γ_s, surface energy of the interface between solid and air) can be obtained by measuring the contact angles ($\theta_1, \theta_2, \theta_3$) of the three liquids (with known surface of γ_1, γ_2, and γ_3 in air) on the solid surface and solving the following three equations deduced from (3)–(6) [6]

$$\gamma_1\,(1 + Cos(\theta_1)) = 2\left({\gamma_1}^{LW}{\gamma_s}^{LW}\right)^{\frac{1}{2}} + 2\left({\gamma_1}^{+}{\gamma_s}^{-}\right)^{\frac{1}{2}} + 2\left({\gamma_1}^{-}{\gamma_s}^{+}\right)^{\frac{1}{2}} \tag{7}$$

$$\gamma_2\,(1 + Cos(\theta_2)) = 2\left({\gamma_2}^{LW}{\gamma_s}^{LW}\right)^{\frac{1}{2}} + 2\left({\gamma_2}^{+}{\gamma_s}^{-}\right)^{\frac{1}{2}} + 2\left({\gamma_2}^{-}{\gamma_s}^{+}\right)^{\frac{1}{2}} \tag{8}$$

$$\gamma_3\,(1 + Cos(\theta_3)) = 2\left({\gamma_3}^{LW}{\gamma_s}^{LW}\right)^{\frac{1}{2}} + 2\left({\gamma_3}^{+}{\gamma_s}^{-}\right)^{\frac{1}{2}} + 2\left({\gamma_3}^{-}{\gamma_s}^{+}\right)^{\frac{1}{2}}\,. \tag{9}$$

Among solids, there are hard inorganic materials such as metal, glass, and ceramic, and soft organic materials. Hard inorganic materials, in contrast to the soft organic materials, have high surface energy, and thus can spread all liquids except mercury. However, contamination can occur, which can change the surface property dramatically. Contamination of a high energy surface with low energy organic contaminants will lead to the decrease of surface energy and raise the contact angle; while, contamination of a low energy surface with high energy contaminants will lead to the increase of surface energy and lower the contact angle.

In a flip chip package, underfill is used to fill the gap between the integrated circuit (IC) chip and substrate or printed circuit board (PCB) to increase the solder joint fatigue lifetime. The adhesion of underfill to passivation layer on IC chip and to solder mask layer on PCB is very important for the reliability of flip chip package. However, delamination (total loss of adhesion) between die and underfill is still a major concern for yield loss and reliability [7], [8]. Delamination at the underfill/die or underfill/substrate interface can lead to cracking of the solder joint interconnection. In a humid environment, water borne contaminants can enter the package through the delaminated area, and cause corrosion of metal pad, joint, and metal line. One of the many possible reasons for poor adhesion is contamination of passivation or solder mask. In order to improve the wetting and thus possibly the adhesion of underfill material with the solder mask and passivation of flip-chip devices, different techniques can be used to clean or modify the surfaces [9], [10]. It is necessary to understand the surface properties before and after treatment processes, and their effect on adhesion.

In this study, the surface properties of solder mask and four passivation materials: polyimide (PI), benzocyclobutene (BCB), silicon oxide (SiO_2), and silicon nitride (SiN) for integrated circuit chips were characterized by measurement of contact angles of the three standard liquids on these substrates after different preparation procedures. The surface atomic composition before and after UV/O_3 cleaning was also investigated through X-ray photoelectron spectroscopy (XPS). In addition, the wetting behavior of underfill on the passivation and solder mask was also studied at elevated temperature. The effect of UV/O_3 and O_2 plasma treatment on the adhesion of epoxy underfill to passivation was also evaluated.

II. EXPERIMENTAL

A. Materials

Deionized water, diiodomethane (99%, from Aldrich Chemicals), and ethylene glycol (99+%, from Aldrich Chemicals) were used as standard liquids for contact angle measurement. The BCB passivated silicon die was supplied by Dow Chemical. The PI passivated dies were supplied by Boeing Company. SiO_2 and SiN wafers were supplied by Silicon Valley Microelectronics. Solder mask from Taiyo was coated on an FR-4 board and cured according to the suggested curing profile from the supplier.

An epoxy underfill (G25) was prepared with one equivalent of cycloaliphatic epoxy resin ERL4221 from Union Carbide, 0.8 equivalent of hardener 4-methylhexahydrophthalic anhydride (MHHPA) from Aldrich Chemicals, and catalyst cobalt (II) acetylacetonate (equal to 0.4% of total weight of epoxy resin and hardener) from Aldrich Chemicals.

B. Surface Preparation Procedures

Wet Cleaning: The steps were as follows: 5 min soak in terpene; 5 min soak in terpene with ultrasonic cleaning; 5 min soak in isopropyl alcohol; 5 min soak in isopropyl alcohol with ultrasonic cleaning; three rinses in deionized water for 2 min each; dry in a vacuum oven at 120 °C for 30 min with a pressure below 30 mmHg.

UV/Ozone Cleaning: UV/ozone(O_3) treatment of the surfaces was performed at 50 °C for 5 min in an UV and ozone dry stripper (Samco, Model UV-1).

O_2 Plasma Cleaning: O_2 plasma treatment was performed with a plasma reactor (Technics Micro-PD series 95) at room temperature for 10 min. The pressure was 150 mtorr. The power was 100 W.

C. Contact Angle Measurement

A goniometer (Model 102-00, from Rame-hart, Inc.) was used to measure the contact angle. A substrate was placed on the sample stage of the goniometer, and a micro syringe was used to deposit a liquid drop of 2–3 μl on the surface of the substrate. The steady-state contact angle was recorded after the

TABLE II
CONTACT ANGLES (DEGREE) OF THREE PROBE LIQUIDS AND UNDERFILL ON SURFACES AT DIFFERENT CONDITIONS

Substrate type	Condition	H_2O	EG	CH_2I_2	G25
PI	as received	90.6	60.9	37.7	32
PI	wet cleaned	59.4	55.9	48.7	29.5
PI	UV/O_3 cleaned without wet cleaning	47.7	6.3	56.6	25
PI	wet cleaned and UV/O_3 cleaned	12	0	22	20.2
PI	wet cleaned and O_2 plasma cleaned	8	0	20	19
BCB	Wet cleaned	87.9	67.3	58.7	14
BCB	wet cleaned and UV/O_3 cleaned	34.6	32.7	64.4	12
SiO_2	wet cleaned	57	46.9	52.9	29.2
SiO_2	wet cleaned and UV/O_3 cleaned	0	0	40.4	11.4
SiO_2	wet cleaned and O_2 plasma cleaned	10	0	31.9	20
SiN	wet cleaned	52.7	39.2	45.4	16
SiN	wet cleaned and UV/O_3 cleaned	0	0	29.9	11.4
SiN	wet cleaned and O_2 plasma cleaned	6	0	29.5	16
solder mask	as received	78.6	52	33.4	35
solder mask	wet cleaned	55	50.5	31	28.1
solder mask	UV/O_3 cleaned without wet cleaning	48	52	46	28.1
solder mask	wet cleaned and UV/O_3 cleaned	12	0	32	15.2

formation of the sessile drop. Five readings were taken for each substrate/liquid combination, and the average was reported.

D. XPS Experiment

An X-ray photoelectron spectroscope (SSX-100-06 from Surface Scientific Laboratory) was used to analyze the surface atomic composition. The monochromatic AlK_α X-ray was used for this study. The incident angle was 45°, and the spot size was 1000 μm.

E. Adhesion Sample Preparation and Test

Silicon dies (2 × 2 mm and 20 × 20 mm) with different passivation [SiN, SiO_2, benzocyclobutene (BCB), or polyimide (PI)] were used to prepare the die shear samples. Glass beads (0.5% weight of underfill), with a diameter of 75 μm, were used as spacers to control the gap between the top and bottom dies. The small die (2 × 2 mm) was dipped onto a thin liquid film of the underfill to coat a uniform thin layer, and then placed on the large die (20 × 20 mm). The die shear samples were then cured at 250 °C for 30 min. For adhesion test between underfill and solder mask, SiN coated silicon dies were dipped onto the thin layer of liquid underfill, and then placed on solder mask coated FR4 board, and the underfill was cured at 200 °C for 60 min. Die shear testing was performed 12 h after the samples were cured. The die shear test was performed on a die bond tester (Model 550-100K, Royce Instruments) with a blade speed of 4 mil/s. The die shear strength is reported in MPa. For adhesion tests at elevated temperature, a heating stage was used, and the temperature of the stage was controlled at the desired temperatures during the die shear tests.

III. RESULTS AND DISCUSSION

A. Contact Angle Measurement of Surfaces After Different Preparation Procedures

Table II lists the contact angles of three probe liquids (water, ethylene glycol, and diiodomethane) on different passivation and solder mask surfaces at different conditions: as received, wet cleaned, and dry cleaned (UV/O_3 or O_2 plasma treatment). The contact angles of water on as-received polyimide passivation and solder mask were high. The wet cleaning treatment removed some contaminants from those surfaces. The contact angle of water on PI decreased from 91° to 59° after wet cleaning, and it decreased from 79° to 55° for solder mask after wet cleaning. The contact angle of water on all "clean" hard surface including SiO_2 and SiN should zero. However, the contact angles of water on the wet cleaned SiO_2 and SiN were not zero in these experiments. This indicated that wet cleaning was not sufficient to clean the surfaces. This is possible due to organic cleaning regents. Dry treatment with UV/O_3 alone without previous wet cleaning also reduced the contact angle of water on PI (from 91° to 48°), and on solder mask (from 79° to 48°). Overall, neither wet clean alone nor dry clean alone was effective enough to remove all the contaminant. The combination of both wet clean and dry clean was very effective, as shown by the great decrease in contact angles of water and ethylene glycol. The contact angles of ethylene glycol on PI, SiO_2, SiN, and solder mask were zero after combined wet and dry cleaning. The wetting of epoxy underfill (G25) on the surface was also improved after cleaning, shown by the decrease of contact angles of underfill on those surfaces.

The surface tension and its three components of those surfaces after different preparation procedures were calculated, and

TABLE III
CALCULATED SURFACE TENSION AND ITS THREE COMPONENTS

Substrate type	Condition	γ_{total} mJ/m^2	γ^{LW} mJ/m^2	γ^+ mJ/m^2	γ^- mJ/m^2
PI	as received	40.94	40.75	0.01	1.70
PI	wet cleaned	38.89	35	0.11	33
PI	UV/O_3 cleaned without wet cleaning	47.31	30.53	2.42	29.11
BCB	Wet cleaned	29.92	29.32	0.02	5.46
BCB	wet cleaned and UV/O_3 cleaned	40.00	26.05	0.87	56.12
SiO_2	wet cleaned	35.82	32.64	0.08	30.98
SiN	wet cleaned	40.32	36.80	0.10	31.99
solder mask	as received	42.76	42.76	0.00	6.70
solder mask	wet cleaned	51.47	43.80	0.43	34.53
solder mask	UV/O_3 cleaned without wet cleaning	43.13	36.47	0.23	48.00

listed in Table III. Young's equation is not valid for the zero contact angle case, thus the acid and base components could not be calculated when contact angle of either ethylene glycol or water was zero. This is the limitation of three-liquid probe method. The base component increased by the greatest amount for most surfaces after UV/O_3 cleaning.

One interesting phenomenon was observed. The contact angle of ethylene glycol on PI passivation did not change much versus age of sessile drop before the passivation was treated with UV/O_3. As a matter of fact, a slight increase of contact angle was observed over a long time due to the absorption of moisture from environment (The volume of the sessile drop increased). However, the contact angle reading decreased significantly with the age of the sessile drop on PI surface after UV/O_3 treatment (Fig. 1). During O_3 treatment, some reactions might take place, possibly including the degradation of the polyimide. The degradation product might be soluble in ethylene glycol, and as the concentration of the degradation product increased in EG, the contact angle reading of the EG (actually it was EG solution if some degradation product was dissolved in EG) on PI would decrease. Another possible reason is that O_3 treated PI can be partially swollen by EG. Thus the contact angle reading decreases with the age of sessile drop.

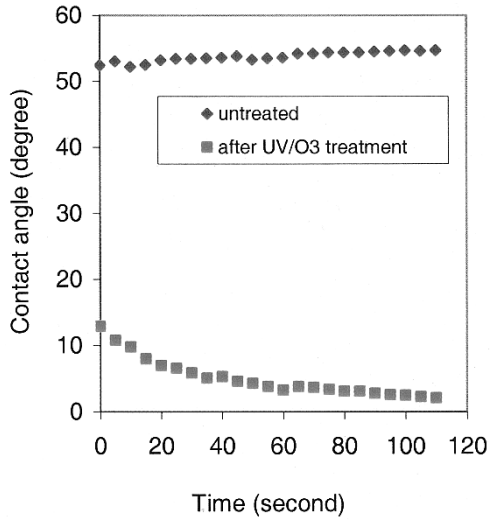

Fig. 1. Contact angle of ethylene glycol on PI passivation before and after UV/O_3 treatment.

B. XPS Analysis of Passivation Surface

The elemental composition of the surface was analyzed with XPS before and after UV/O_3 treatments. Fig. 2 shows XPS spectra of BCB passivation before and after UV/O_3 treatment. The peaks due to photoelectrons of Si_{2p}, Si_{2s}, C_{1s}, O_{1s}, and oxygen Auger (O_a) peak are marked in graph (a) in Fig. 2. Obviously, it can be seen from the spectra that the carbon concentration decreased dramatically after the UV/O_3 treatment. The intermediate product of both formation and decomposition of O_3 is atomic oxygen, a very strong oxidizing agent. The UV/O_3 treatment can oxidize the organic contaminants and remove them from the surface. At the same time, it can also oxidize the organic passivation and solder mask. Removal of hydrocarbon contaminants and oxidation of organic passivation will increase the relative concentration of oxygen and reduce the relative concentration of carbon on the surface.

The relative concentrations of the elements on the surface were calculated, and they are listed in Table IV. The concentration of carbon at the surface decreased for all materials tested after UV/O_3 treatment. Also, it can be noticed that oxygen concentration increased after the UV/O_3 treatment of the surface, except in the case of SiN. It was shown earlier that the base component of the surface tension increased dramatically after UV/O_3 treatment. This increase in base component is due to the increase of oxygen on surface due to the UV/O_3 treatment. For silicon nitride, its major elements, silicon and nitrogen, increased most after the UV/O_3 treatment. It should also be noticed that there were still significant amounts of carbon on the surface of SiO_2 and SiN even after UV/O_3 treatment, even though the contact angles of water on the UV/O_3 treated SiO_2 and SiN were zero. It can be seen form Table IV that there was Si in the polyimide and BCB of this study. In microelectronic industry, O_2 plasma containing $\sim 20\% CF_4$ or other fluorine containing gas is usually used to descum the Si containing BCB or PI via [11]. If no-fluorine containing O_2 plasma is used for the descum process, SiO_2 layer may form on the top surface, and prevent further descum process of the O_2 plasma. In this

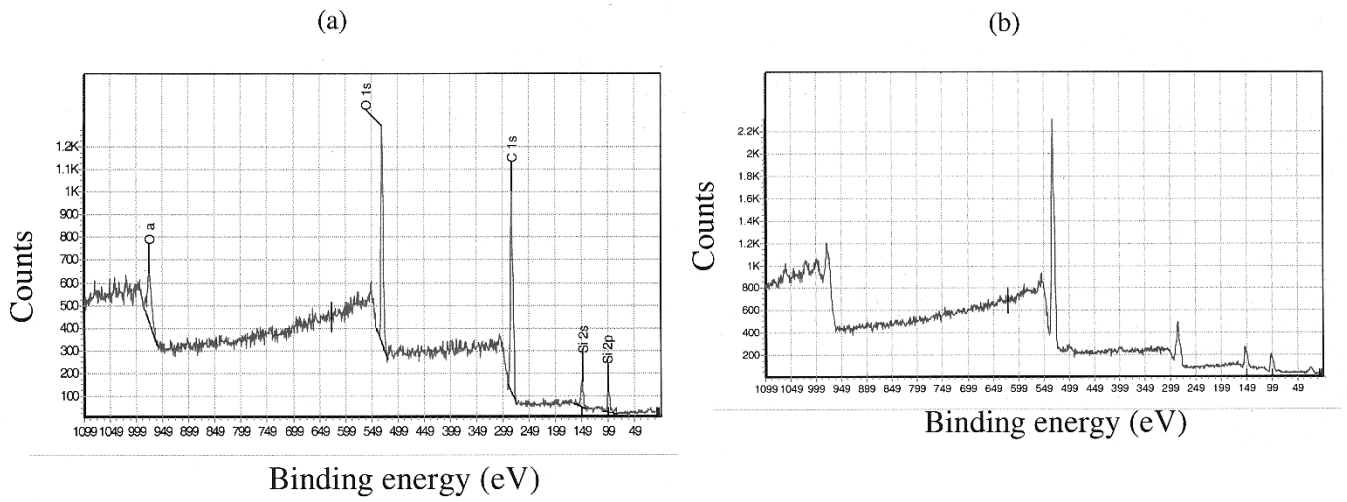

Fig. 2. XPS spectra of BCB: (a) before UV/O_3 cleaning and (b) after UV/O_3 treatment.

TABLE IV
RELATIVE SURFACE ELEMENTAL CONCENTRATION OF DIFFERENT MATERIALS

Materials	Condition	C	N	O	Si
PI	wet cleaning	77.1	-	15.6	7.33
PI	wet cleaning + UV/O_3 cleaning	34.7	-	52.9	12.4
BCB	wet cleaning	62.6	-	27.7	9.7
BCB	wet cleaning + UV/O_3 cleaning	30.5	-	55.9	13.5
SiO_2	wet cleaning	18.1	-	53.5	28.5
SiO_2	wet cleaning + UV/O_3 cleaning	11.6	-	56.9	32.6
SiN	wet cleaning	20.2	25.9	23.3	30.7
SiN	wet cleaning + UV/O_3 cleaning	13.1	29.3	22.7	34.9
Solder mask	wet cleaning	69.4	-	30.6	-
Solder mask	wet cleaning + UV/O_3 cleaning	52.0	-	48.0	-

study, UV/O_3 was used to clean hydrocarbon contaminant on the passivation or solder mask surface. The Si and O concentration on PI and BCB surface increased after UV/O_3 cleaning process, and this indicated that some Si-O bonds might form during UV/O_3 cleaning process.

The UV/O_3 treatment made the surfaces more hydrophilic as indicated by the low contact angle of water on those surfaces. However, if the treated samples were left in a normal lab environment, the contact angle of water or ethylene glycol on the surface increased versus time. This behavior is called hydrophobic recovery. For inorganic materials such as SiO_2 and SiN, the hydrophobic recovery is due to recontamination by hydrocarbon in the environment. In addition to the recontamination, there are some other possible mechanisms for hydrophobic recovery of the UV/O_3 treated organic surface after the treatment. One is polar group reorientation at the surface. The rate of polar group reorientation depends on the mobility of molecules at the surface, and thus depends on the temperature of the environment and the glass transition temperature of the polymers (BCB, PI, and solder mask). Also, the diffusion of low molecular weight species from the bulk to the surface was suggested to be one possible reason for the hydrophobic recovery [12]. Among all the possible reasons, the most important one is the recontamination from the environment. The contamination of the surface by hydrocarbon from the environment will cause the increase of contact angle. The glass transition temperature of all these materials (BCB, polyimide and solder mask) are all well above room temperature, so the reorientation is not likely. The reorientation of the polar group is initiated by the medium. However, the medium is O_3 during UV/O_3 treatment and air before and after UV/O_3 treatment. No important factor can introduce polar group reorientation. Low molecular weight species diffusion is not likely. Some samples were kept under ultrahigh vacuum in XPS chamber $(pressure < 10^{-8}\ torr)$ for 24 h, and no change in surface elemental concentration was detected either for UV/O_3 treated or untreated samples.

TABLE V
ADHESION STRENGTH (MPa) OF UNDERFILL TO DIFFERENT PASSIVATION

Surface	Untreated	UV/O_3 treated	O_2 plasma treated
PI	42.8±12.2	40.3±6.7	41.8±11.1
BCB	38.3±8.3	37.3±10.5	-
SiO_2	56.0±8.0	63±9.7	54±6.6
SiN	60.0±7.6	58.7±6.4	55.2±14.3
Solder Mask	32.9±6.2	29.1±7.9	-

C. Wetting of Underfill at Elevated Temperatures

It was attempted to measure the contact angle of the three standard liquids on the surface of solder mask and different passivations. However, the evaporation of water and diiodomethane was very fast at elevated temperature during contact angle measurement, thus the equilibrium contact angles for these two liquids could not be obtained. Ethylene glycol is less volatile, and the equilibrium contact angles of ethylene glycol on those surfaces were measured at elevated temperature up to 120 °C. It was observed that the contact angles of ethylene glycol on those surfaces all decreased with the increase of temperature. The contact angles of underfill on passivation and solder mask at elevated temperatures were also measured. Contact angles of underfill decreased steadily with the increase of temperature, indicating the wetting became slightly better at higher temperatures. This is mainly due to the increased thermal motion of molecule at high temperatures. However, the adhesion strength of cured underfill with passivation decreased with the increase of temperature, which is mainly due to the decrease of underfill modulus with increase of temperature [13].

D. Effect of UV/O_3 Treatment on Adhesion

The adhesion of underfill to different passivations was studied with die shear test. In the case that passivation is treated with UV/O_3 or plasma for adhesion sample preparation, all the die shear samples were prepared immediately after the UV/O_3 or O_2 plasma treatment. Preparation of samples can be finished within 3 min after the UV/O_3 treatment to minimize the recontamination. From the results shown in Table V, it can be seen that there is no significant improvement in adhesion strength after the UV/O_3 treatment or O_2 plasma treatment, although significant improvement in wetting of underfill on the passivation materials was observed after UV/O_3 or O_2 plasma treatment [Table II]. This behavior may be explained as follows. Without dry treatment, a thin layer of hydrocarbon is absorbed on the surface of passivation material, and thus the wetting of underfill on passivation is hampered. With the dry treatment, this thin layer of hydrocarbon is removed, and thus the wetting is greatly improved. The curing of underfill is performed at high temperature 250 °C. During the heating, the absorbed hydrocarbon can desorb from the surface and be dissolved in the underfill materials. Thus, even without dry treatment, this thin layer of hydrocarbon does not exist at the interface after the curing of underfill. Thus no significant difference was observed between untreated sample and treated sample. Wetting is very important for adhesion on a rough surface, as good wetting is needed to fill the asperity on the surface, thus increasing the total contact area and reducing the void at interface. Apparently, when the surface is very smooth, the wetting is not the controlling factor for adhesion.

IV. CONCLUSION

A combination of wet cleaning and dry cleaning was very effective to remove the contaminants from the surface. X-ray photoelectron spectroscopy experiments confirmed the increase of oxygen concentration on the surface after UV/O_3 treatment, which led to the increase of the base component of surface tension. In addition, wetting of the underfill on passivation and solder mask became slightly better at higher temperatures. Although UV/O_3 cleaning and O_2 plasma treatment significantly improved the wetting of underfill on the smooth passivation and solder materials, they did not show improvement in adhesion strength.

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